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Foundation Response to Subsidence-Induced Ground Movements: A Case Study

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BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	mm/m	millimeter per meter
in	inch	μrad	microradian
km	kilometer	pct	percent
min	minute		

FOUNDATION RESPONSE TO SUBSIDENCE-INDUCED GROUND MOVEMENTS: A CASE STUDY

By Jeffrey S. Walker[1] and John C. LaScola[2]

ABSTRACT

The purpose of this U.S. Bureau of Mines effort was to determine if ground movement caused by mining-induced subsidence is directly transferred to a structure and, if so, how that transfer takes place. Four concrete block walls with foundations were constructed and monitored over an active longwall panel. Three of the walls were located perpendicular to the direction of mining in zones where maximum inclination, maximum tension, and maximum curvature were predicted to occur. The fourth wall was constructed along the centerline of the panel, parallel to the direction of mining. All of the walls and the surrounding ground surface were instrumented with conventional survey monitoring points and extensometer stations to observe the vertical and horizontal movements. The fourth wall instrumentation also included continuously recording tiltmeters. The results of this investigation indicate that these simple structures respond to subsidence in a similar manner as the ground surface. This suggests that once the transfer mechanism is more fully defined, prediction models can be developed to accurately estimate the effect of mining on surface structures.

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INTRODUCTION

Damage to surface structures as a result of mining-induced subsidence has been a concern of coal operators and landowners for many years. In the past, most mine subsidence events were unplanned, occurring when support pillars failed in abandoned mines long after coal removal. With the increasing use of full-extraction mining methods, which cause surface ground movements contemporaneous with mining, there is a growing public concern about the effect of these movements on surface structures and other features. With more and more longwall mine operators planning to undermine populated areas, it is expected that this issue will become one of the most important considerations for mine planners and regulatory officials.

At present, mine operators establish the layout of their mines to avoid longwall mining under surface structures whenever possible, using more costly and less efficient room-and-pillar methods under populated areas so that support pillars can be left without severely altering production. However, as mining in areas with few surface structures becomes less available and the economic need for high-extraction mining increases, it becomes obvious that methods to protect surface structures, when using full-extraction mining methods, need to be developed.

Today, longwall mine operators have two options available for addressing surface damage: (1) protect surface structures by varying the panel dimensions, or (2) negotiate repair or purchase agreements with landowners whose property may be damaged by mining activities. Neither of these options is especially attractive. The first may cause a loss of resources and produce irregular mine layouts detrimental to future mining. The second option can significantly add to the cost of mining.

The Bureau of Mines has initiated a program to assist the mining community in the prediction of mining-induced stresses that may be transferred into a surface structure. Very little information is presently available concerning the surface effects and amount of damage that can be expected as a result of mining. The information that is available is usually based on European methods and, like European subsidence prediction models, may not be directly applicable to the conditions existing in the United States *(1)*.[3] The concept of the Bureau's program is to monitor the movements of both existing and specifically designed structures in response to mining-induced subsidence to determine the mechanism for the translation of ground strains into a structure. Once an understanding of this mechanism is established, it may be possible to modify existing subsidence prediction models to predict mining-induced strains in surface structures.

To accomplish this goal, a pilot project was initiated to record the movements of surface structures and the adjacent ground. Four concrete walls and foundations were constructed on the surface above an active longwall panel and were instrumented with an array of tiltmeters, extensometers, and subsidence monitoring stations. This report presents an analysis of the data obtained from the pilot study. The basis of this analysis was the comparison of measurements taken from the walls and ground monument arrays, as well as the comparison of calculated and true inclination values recorded by the tiltmeters.

PROJECT CONSIDERATIONS

It is widely recognized that the vertical displacement associated with subsidence causes little appreciable damage to structures, so long as the magnitude of the movement is uniform across the length of the structure. The most commonly observed subsidence damage is caused by the horizontal tensile and compressive strains associated with the bending of the ground surface *(2)*. In subsidence engineering, bending of the ground surface is discussed in terms of inclination or tilt, and curvature. When analyzing the stresses on a structure caused by mining, it is necessary to address the stress generated by both the advancing subsidence wave and the development of the subsidence profile. In a static sense, it is possible to predict subsidence parameters based on vertical displacement, and with a sufficient degree of confidence, estimate the postmining tilt and ground strain at any surface point along a subsidence profile *(3)*. However, it is much more difficult to predict ground movement at any particular moment during mining because of a lack of information concerning the exact shape of the developing subsidence wave. These considerations were included in the design of this project.

[3]Italic numbers in parentheses refer to items in the list of references at the end of this report.

SITE DESCRIPTION

The study site selected was located in Barbour County, WV (fig. 1). The surface area consisted of fairly level land over a 1,000-ft-wide longwall panel (fig. 2). The depth to mining was approximately 650 ft, and approximately 6 ft of coal was extracted. The overburden lithology consisted of fine-grained sedimentary rock with numerous massive sandstone units, composing 37 pct of the total thickness (fig. 3).

Four masonry walls were constructed over the longwall panel in areas where maximum subsidence effects, such as compression, tension, and inclination, were predicted by the Bureau's subsidence prediction model (fig. 4) *(4)*. The longest wall (wall A), termed the dynamic wall, was located along the centerline of the panel parallel to the long axis. This wall was specifically placed so that it would flex in response to the advancing subsidence wave. The remaining three walls, termed static walls, were placed perpendicular to the advance of the longwall face. The specific locations of the walls relative to the panel were calculated, prior to mining, to be in areas of maximum compression (wall B), maximum inclination (wall C), and maximum tension (wall D) (fig. 5).

Concrete block walls were chosen as the type of structure to be monitored for this study in order to simplify analysis. The walls were constructed in a manner typical of foundation construction in the area. Each wall was constructed of standard, single-web concrete block, on an unreinforced concrete strip foundation. Pilasters were keyed into the wall on 12-ft centers to increase stability. The footing was 4 in thick and approximately 30 in wide. Because the walls were not loaded, 4- by 4-in ribs were formed into the bottom of the footing to increase the bond with the soil. The footing was placed on a level subgrade in a firm, brown silty-clay soil below the original surface. The dimensions for the four walls are given in table 1.

TABLE 1.—Wall dimensions, feet

Type of structure	Length	Height
Dynamic wall	86.33	4.0
Static wall:		
Tension	36.0	4.66
Compression	36.0	4.66
Curvature	36.0	4.66

Figure 1.—Index map.

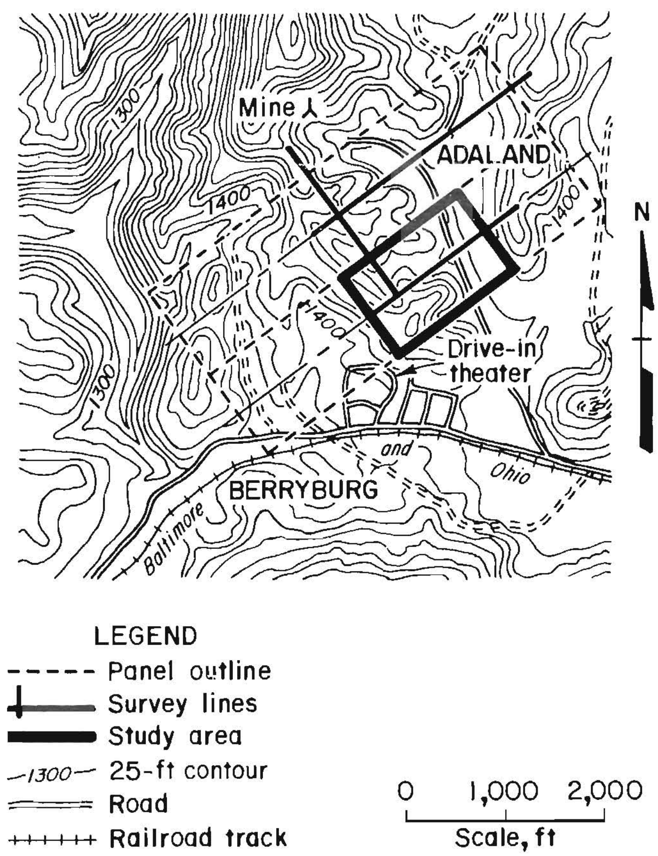

Figure 2.—Site plan.

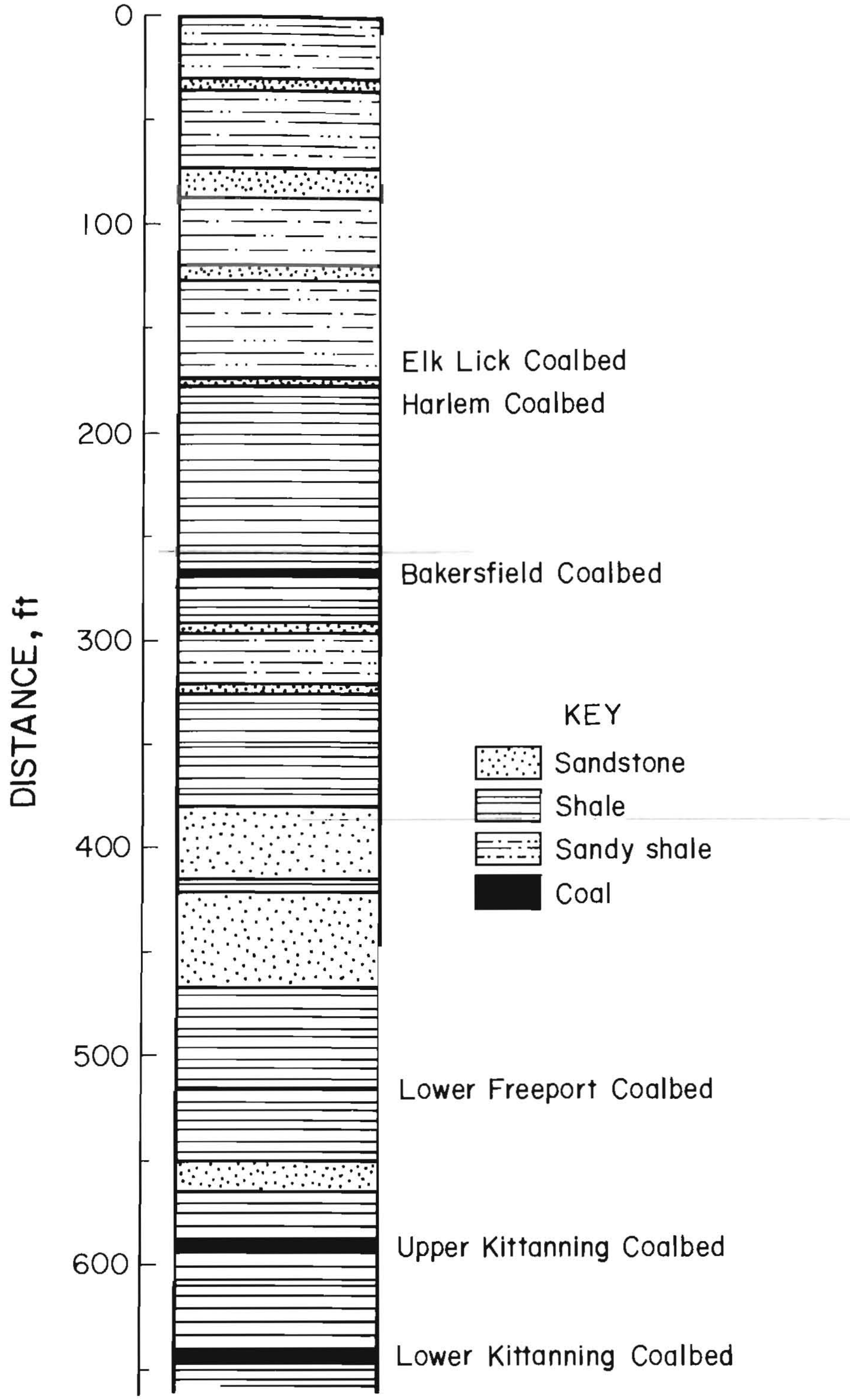

Figure 3.—Generalized stratigraphic column.

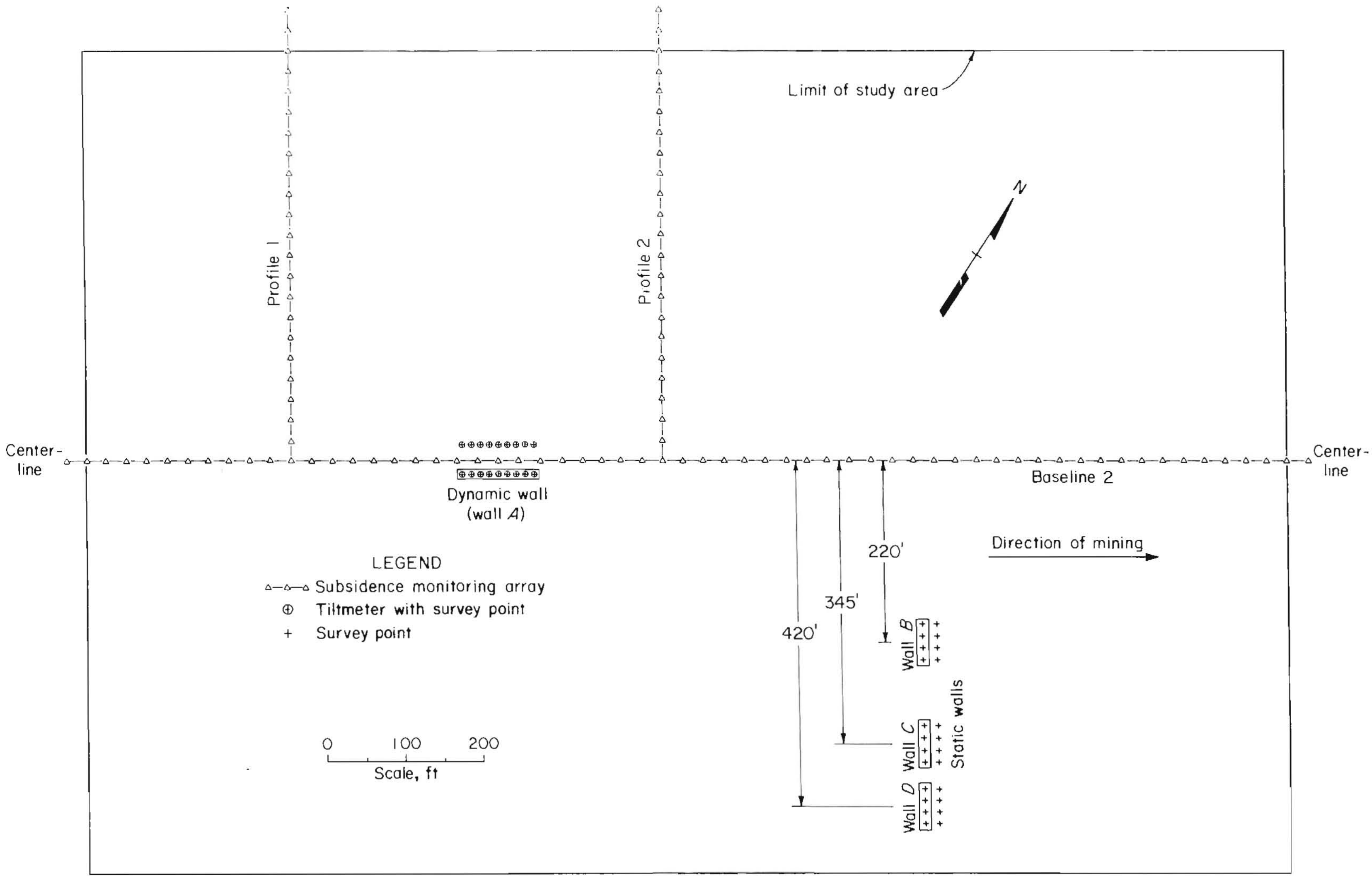

Figure 4.—Study area.

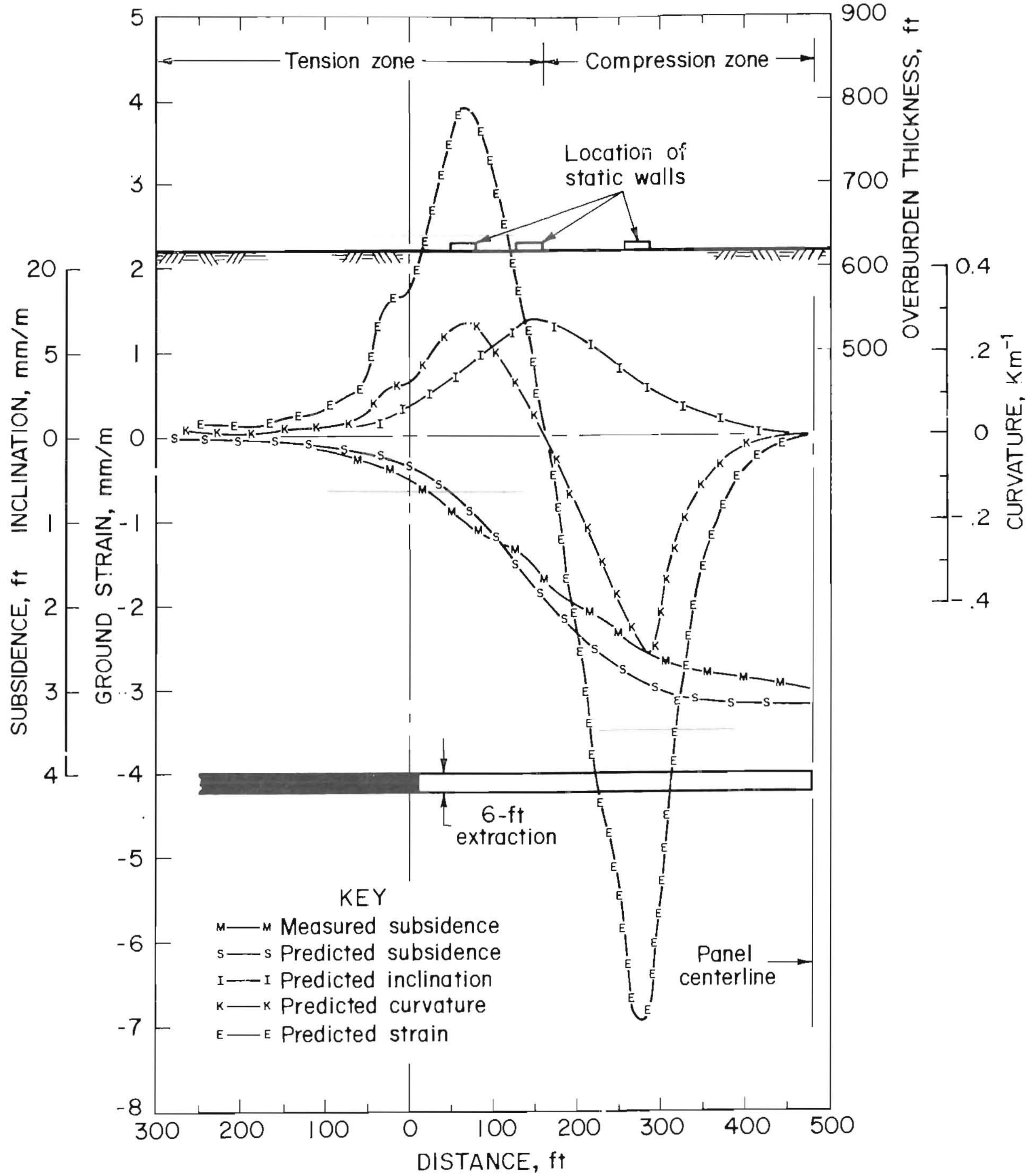

Figure 5.—Predicted subsidence values.

MONITORING PLAN

This foundation response project was part of a larger study to monitor subsidence over two adjacent longwall panels. Subsidence monitoring grids, consisting of a 1,500-ft baseline coincident with the centerline of the longwall panel and two perpendicular profile lines, were established above each panel (fig. 4). During the 60-day period when the walls were undermined, survey data were collected from each wall and the ground surface arrays on a regular basis to detect both vertical and horizontal displacement. The dynamic wall had additional instrumentation to continuously measure the inclination during critical portions of the study period.

The static walls were primarily designed to show the effects before and after mining (fig. 6). Survey monuments were set as pairs in the top of the pilasters and in the ground at locations parallel to the axis of the walls. These points were monitored on a weekly basis to observe the movement of the walls relative to the ground surface. Additional points were installed on the base of each pilaster as extensometer mounting points. A tape extensometer was used to measure movements in the walls caused by ground deformation.

The instrumentation for the dynamic wall was designed to continuously collect information. It consisted of a control line of tiltmeters installed in the ground and an identical set installed in the wall, along with survey monitoring points and extensometer stations as described for the static walls (fig. 7). Each tiltmeter was programmed to record tilt in the X-Y plane at 10-min intervals throughout the period of expected movement and on a less frequent basis after more than 90 pct of the predicted maximum subsidence was achieved. The elevation and spatial location of the tiltmeters were measured weekly using standard surveying procedures.

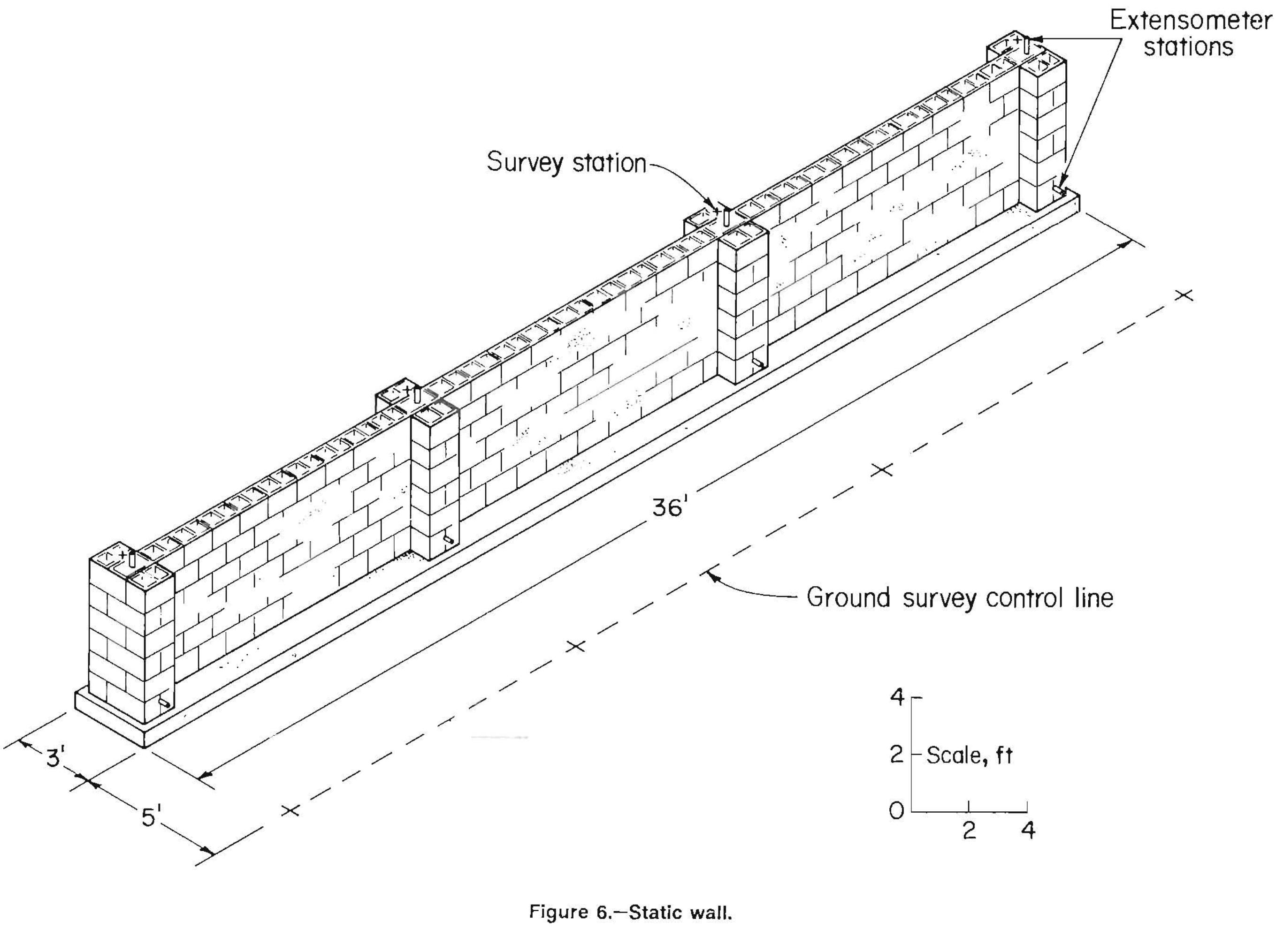

Figure 6.—Static wall.

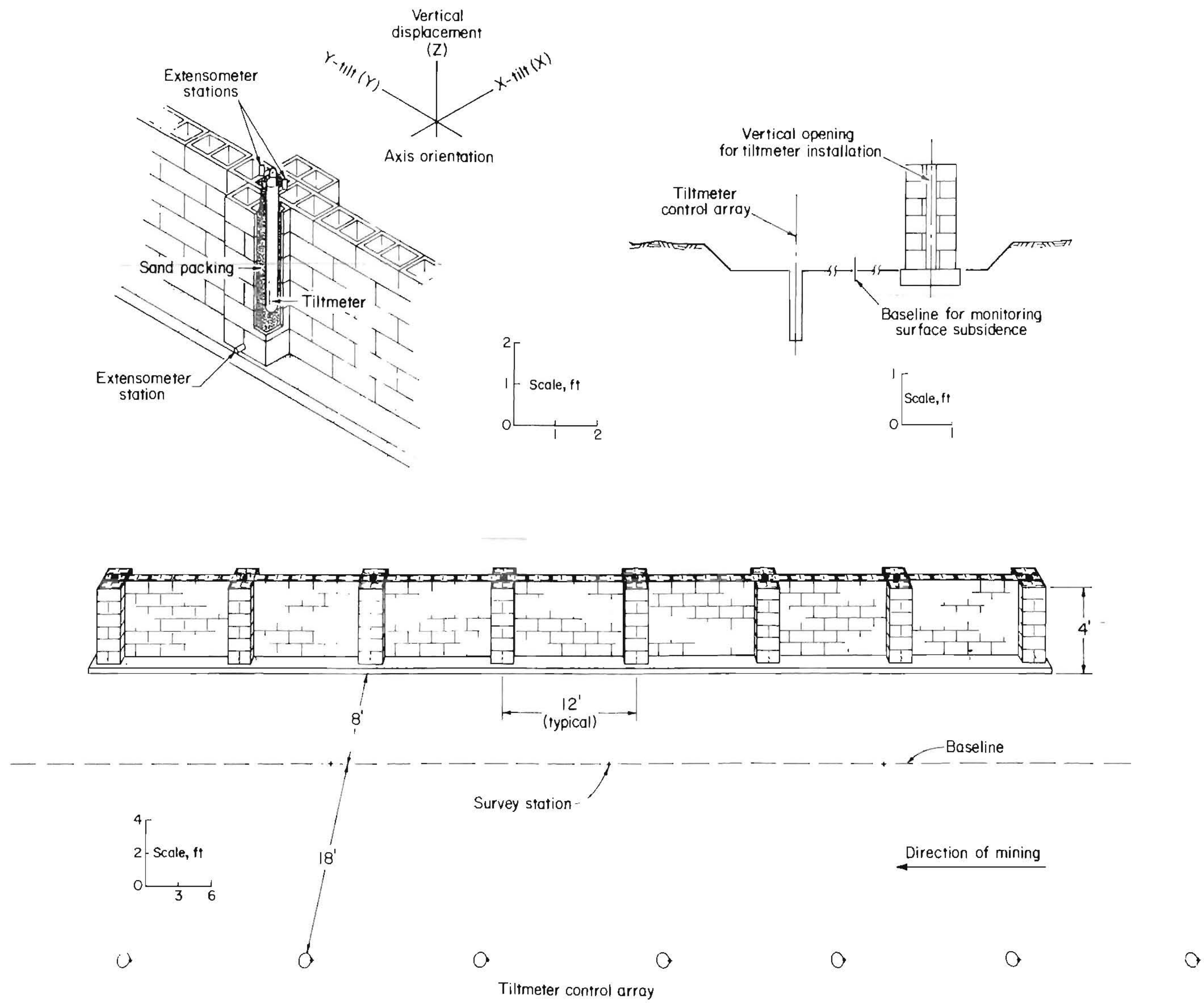

Figure 7.—Dynamic wall.

The tiltmeters were AGI-700 borehole mount units controlled by a microprocessor-controlled data logger.[4] The tiltmeter data were collected on cassette tape recorders and then transferred to the Bureau's computer system. The tiltmeters were capable of measuring 0° to 4° of tilt in both the X and Y direction with a sensitivity of 1 μrad *(5)* (1 μrad of tilt is equal to 0.001 mm/m or $5.73° \times 10^{-5}$). The tiltmeters in the wall were installed in vertical openings in each pilaster, and those in the ground were installed in 5-ft-deep boreholes cased with 6-in-diam polyvinyl chloride pipe. Moist sand was placed around the instruments to secure them in the openings and to allow initial leveling. Leveling was accomplished by tamping additional layers of sand around the tiltmeter until the instrument was level and firmly coupled with the surrounding medium.

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

RESULTS

STATIC WALLS

The three static walls were deformed by subsidence, but did not show any signs of failure. No cracks were observed in either the masonry or the concrete footing. The final subsidence measured along the profile where the walls were located was similar to the value predicted by the Bureau's model (fig. 8). As predicted and designed, the walls were correctly located in the areas of maximum compression, maximum inclination, and maximum tension.

The movement parameters collected from the static walls are shown in table 2. The predicted parameters are based on the predicted ground movements using the Bureau's model.

Measurements of walls B and D, located respectively in the zones of maximum compression and maximum tension, showed them to have the greatest curvature. These curvatures did not generate sufficient angular distortion over the length of the wall to cause bending failure. Wall C was subjected to only one-half the bending stress measured at static walls B and D, resulting in proportionally less deflection.

None of the movement parameters measured for the static walls agreed with the parameter values obtained from the Bureau's subsidence prediction model, although the shapes of the curves were similar. In all but one case, the measured values were less than the predicted values.

DYNAMIC WALL

The dynamic wall was located along the centerline of the panel where it would be subjected to the extreme of the various stresses associated with the advancing subsidence wave. The wall and ground subsided in a similar manner a total of 3.26 ft. The difference between the vertical displacement of the wall and the ground was 0.01 ft or less in 80 pct of the measurements. A maximum difference of 0.75 ft in elevation was measured between the leading and trailing edge of the wall when the longwall face was 310 ft beyond the wall. As a result of the changing ground surface, the wall broke into three approximately equal pieces (fig. 9). Failure cracks were observed in the footing and mortar joints of the wall. The actual development of the cracks was not observed, but their patterns are shown in figure 10.

The shape of the advancing subsidence wave was determined by repeatedly measuring the vertical displacement along the baseline and plotting the values relative to the position of the longwall face. The results of these surveys are shown in figure 11. A hyperbolic tangent function was fit to the vertical displacement data. Analysis of this curve indicates that very little subsidence occurred prior to the wall being undermined. When the longwall face was approximately 100 ft ahead of the midpoint of the wall, 0.1 ft of subsidence was measured; only 0.3 ft of subsidence was measured when the face passed directly beneath the midpoint of the wall. Approximately 95 pct of the maximum subsidence had occurred once the face was 550 ft beyond midpoint of the array. The inflection point of the curve occurred when the face was approximately 220 ft beyond the midpoint of the array. The maximum tensile and compressive strains were estimated to have occurred when the face was 100 ft ahead to 175 ft beyond the midpoint and 225 to 500 ft beyond the midpoint, respectively. It is possible to use the mathematical relationship between subsidence and inclination and subsidence and curvature to estimate these parameters for the advancing subsidence wave. Table 3 shows the comparison of estimated, calculated, and measured tilt for both the ground and the dynamic wall.

The estimated value was obtained by differentiating the curve fitted to the face curve with respect to X, then setting X equal to the distance of the face from the center of the array. The calculated values were obtained by using the measured vertical displacement values for the leading

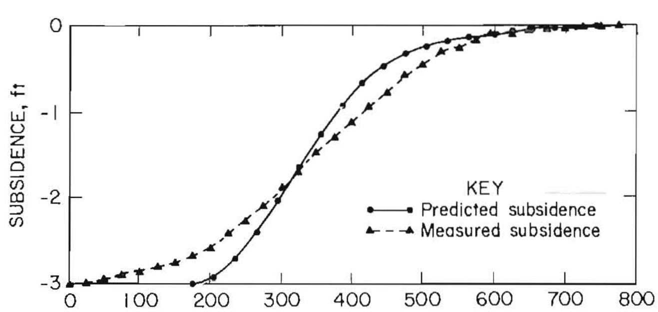

Figure 8.—Comparison of predicted and measured subsidence.

TABLE 2.—Predicted and measured movement parameters for static walls

Wall and area	Subsidence, ft	Inclination, mm/m	Curvature, km^{-1}
B (max. compression):			
Predicted	3.46	4.70	0.68
Measured	2.50	1.93	.46
C (max. inclination):			
Predicted	1.77	13.70	.45
Measured	1.68	8.60	.23
D (max. tension):			
Predicted	.95	5.33	.68
Measured	.80	9.30	.46

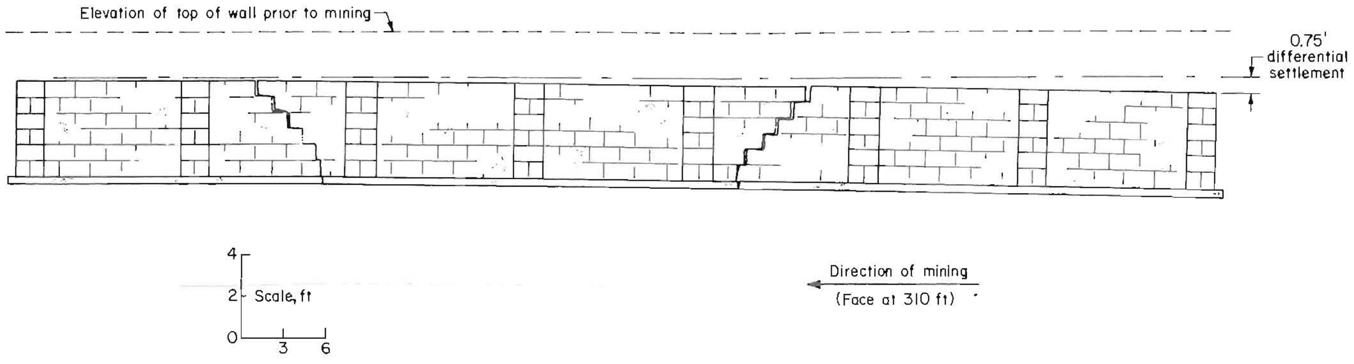

Figure 9.--Schematic of dynamic wall at failure.

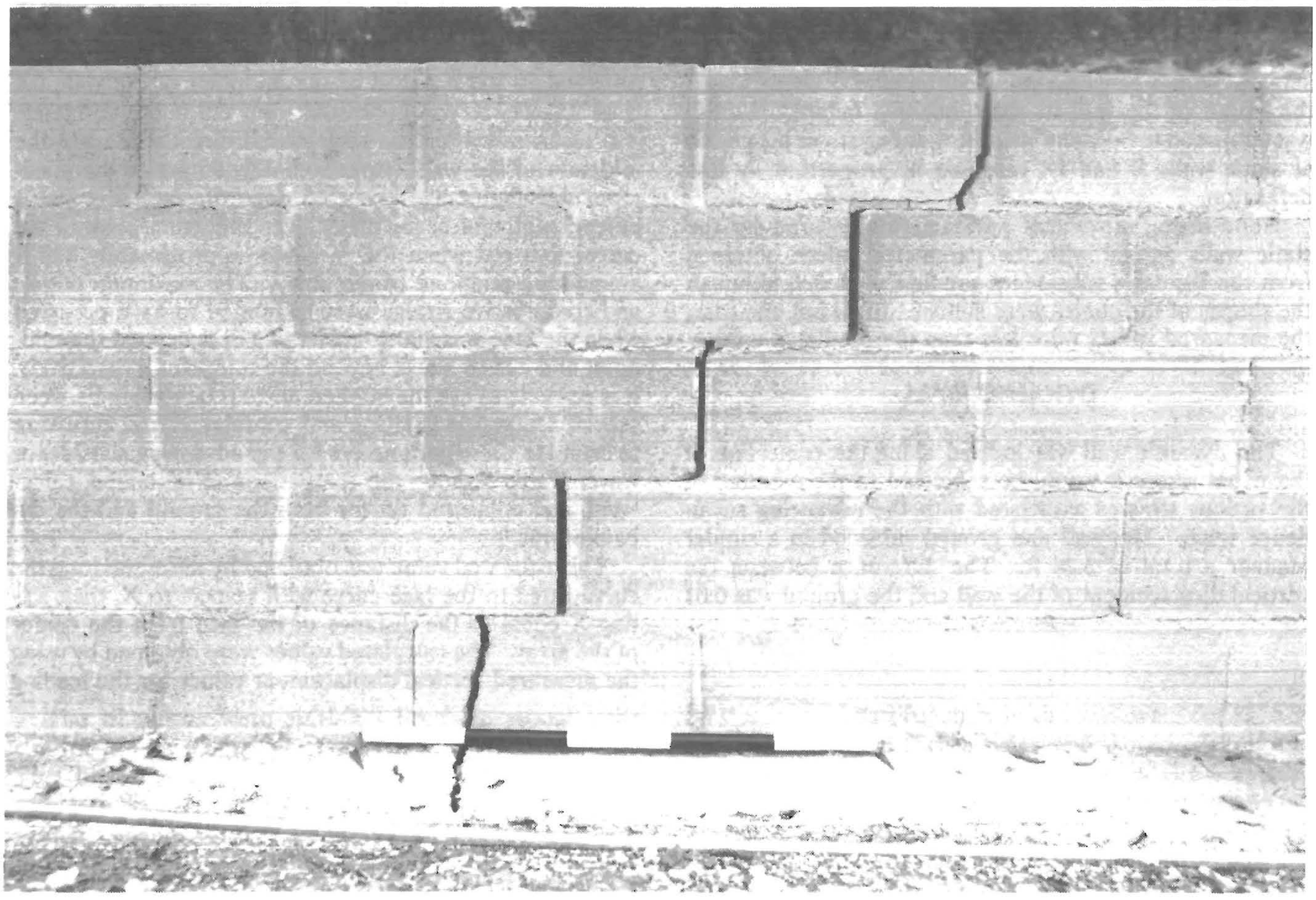

Figure 10.—Failure crack.

and trailing ends of the array to calculate the tilt at the midpoint of the array. The measured value is the average tilt measured by the tiltmeters in each array.

The shape of the curve generated by the tiltmeter data is similar to the estimated inclination curve with slight variation (fig. 12). The magnitude of the tilt, the minimum point, and the endpoints of the curves generally agree. A tilt of approximately 2 mm/m was indicated by the tiltmeter data after subsidence was complete. Further investigations are necessary to determine if the residual tilt may have resulted from the installation of the tiltmeters after subsidence had been initiated or if it is related to the subsidence process.

Comparison of tilt measurements indicates that the tilt of the wall averaged 1.5 mm/m less that the tilt of the ground. Also, the tilt in the wall lags behind the ground tilt, in both the initial movement and recovery, suggesting that the wall resists the deflection caused by the advance of the subsidence wave.

The direction and timing of the cracks in the dynamic wall can be expressed as tension failure resulting from extreme positive curvature or upward deflection *(6)*. Failure of this type is characterized by cracks running diagonally outward (fig. 9). The greatest curvature observed at the wall occurred when the face was 110 ft beyond the wall midpoint. It can be assumed that the wall failed at this time. Horizontal extension values for the dynamic wall at various face positions are shown in table 4. The extensometer readings indicate that as the wall was undergoing positive curvature, strains as high as 16.58 mm/m and 15.08 mm/m were measured across wall sections where failure occurred. During the period of negative curvature the wall was not observed to compress a measurable amount.

TABLE 3.—Estimated, calculated, and measured tilt for both ground and dynamic wall, millimeters per meter

Distance from midpoint of wall, ft	Estimated	Calculated		Measured	
		Wall	Ground	Wall	Ground
0	2.88	1.13	1.00	NA	NA
110	6.53	6.75	7.38	4.00	4.40
270	8.47	8.12	9.37	10.01	10.07
410	3.75	3.63	4.25	7.08	6.55
530	1.24	2.13	2.13	3.48	3.15
760	1.14	1.38	1.25	1.95	1.50
930	0	1.00	1.00	NA	NA
1,040	0	1.00	1.00	NA	NA

NA Not available.

TABLE 4.—Horizontal extension values for the dynamic wall at various face positions, millimeters per meter

Distance from midpoint of wall, ft	Estimated	Calculated	Measured	
			Wall	Ground
0	0.24	0.96	0.01	0.03
110	.36	1.24	.00	.06
270	-.24	-1.24	.01	0
410	-.36	-.96	.02	-.05
530	-.12	-.024	.05	-.12
760	0	-.24	.05	-.12
930	0	.48	.10	-.13
1,040	0	.96	.10	-.15

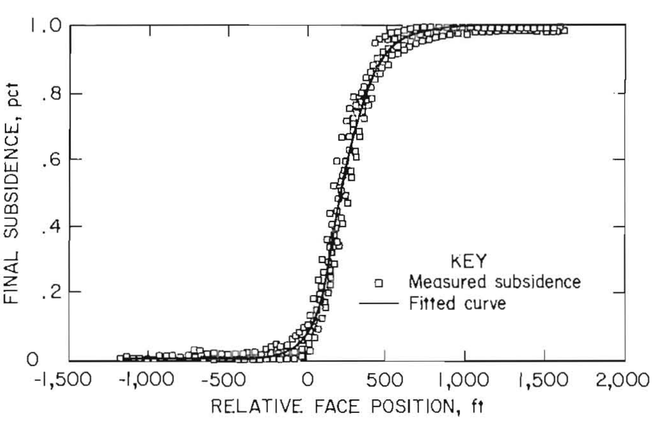

Figure 11.—Advancing subsidence wave.

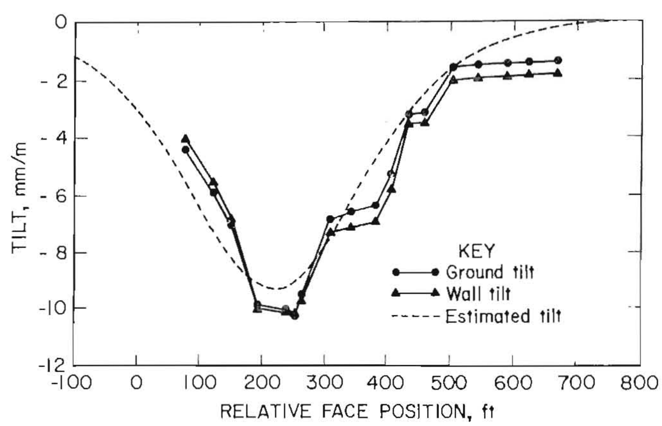

Figure 12.—Comparison of estimated and measured tilt.

SUMMARY AND CONCLUSIONS

The purpose of this investigation was to monitor the differences between the movement of a simple surface structure and the ground surface in response to mining-induced subsidence. In comparing the measurements made for the static walls and the adjacent ground surface, it was found that although the ground and the wall moved in a similar manner, the movement measured at the wall was less than the ground. The continuously recording tiltmeters in the dynamic wall indicated that the advancing subsidence did in fact pass through both the wall and the ground in a wavelike motion. However, the inclinations observed in the wall and the ground were not identical. The shapes of the curves were similar, but the average tilt measured for the wall was 1.5 mm/m less than the ground, and exhibited a slight time lag. As a result of the changing ground surface, the dynamic wall broke into three approximately equal sections. The orientation and timing of failure cracks suggest that the wall failed in tension because of extreme positive curvature. Comparison of the measured and predicted values for the walls indicates that the curve shapes for subsidence, inclination, and curvature agree but vary in timing and magnitude.

Based on this investigation the response of a simple surface structure to mining-induced ground movements appears to be similar to that of the ground surface. This case study is a first step towards understanding the mechanism that transfers mining-induced ground stresses to surface structures. Given enough field data, it is believed that a conceptual model can be constructed that will allow mine operators to evaluate surface deformations and the impact to structures in advance of mine development.

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